ABSTRACT: We established an industrial solar cell process for mono- and multicrystalline 156×156 mm² silicon solar cells in a research center (ISC Konstanz). With a stable baseline process, cell development can be interconnected with industrial production standards. Easy monitoring of process stability, material testing and a standardized reference processes is achieved. Developed processes on a laboratory level can be tested with respect to industrial stability. We exemplify a learning curve, how an adequately stable process can be established in a laboratory environment. Monitoring is crucial, so we have introduced several fixed characterization steps into the baseline process. As examples, material testing and optimization of the co-firing in the baseline process are shown.

Keywords: Experimental Methods, Monitoring, Baseline
Process interruption of the texturing process leads to changing process conditions, lowering process velocity after restarting the process. This is caused by missing nitrogen monoxide, which during texturing reacts with nitric acid to nitrous acid. Nitrous acid reacts significantly faster with silicon than nitric acid. Furthermore, the appearance of the wafer surface during process ramp up is different.

Screen printing at the ISC Konstanz is not reaching the same cycle time as in industry. Manual loading is time consuming, limiting the throughput for three printing steps to about 200 cells per day. Therefore, screen printing pastes are dosed in smaller amounts. They are infrequently sheared by the squeegee and remain comparatively long on top of the screen. This leads to faster evaporation of solvents. Thus screen printing at an institute is slightly different compared to mass production.

3 PROCESS DETAILS

3.1 Standardized process steps

For a baseline run, it is essential to keep all processes (as much as possible) the same. One might consider this obvious and easy to achieve – “just do the same over and over again”. But, for example, different wafer material can lead to differences in efficiency of more than one percent absolute. Especially in a research environment, where different processes are run on the same machine, this topic turned out to be very serious. Among others, we found the following standardized steps to be crucial for successfully running a baseline process.

All wafers have to be numbered, ideally indicating the ingot position.

Known wafer material has to be used for all baseline runs. Therefore, neighboring wafers for baseline runs lasting the next years have to be in stock. For the mc-Si baseline run discussed here, we have selected 2000 wafers and homogenized them. This yields material for 40 baseline runs. After analyzing the results of the first runs regarding the distribution of cell parameters, the influence of the material becomes obvious. This analysis is necessary to interpret the process stability of all following baseline runs.

In our experiments we always use a detailed standard run protocol. Only dates and times can be changed. For each process step, there are non changeable machine recipes for the baseline run. Wherever it might be important, no room is left for individual variations by the operators. For example orientation of and waiting time in between subsequent cells are defined for contact firing. Baseline runs have to be performed regularly to detect changes in processes. At the ISC Konstanz, this baseline process is run and analyzed at least every six weeks.

Furthermore quality management is necessary. For example regular checks of cleanliness of the diffusion tube, cleanliness of chemical baths or the quality of the printing screens.

3.2 Characterization steps

Similar to the process steps (3.1), standardized characterization has to go along with the baseline run. The settings of characterization equipment have to be defined in the run protocol. For IV measurements, it is...
best to put aside reference cells, solely for characterization of baseline cells.

Characterization steps for the described baseline process are mainly
- measurement of texturization depth,
- measurement of sheet resistance after diffusion with PSG,
- optical analysis of SiN layer,
- weight of pastes during screen printing,
- determination of finger width and -height of the front side grid after firing,
- IV measurements and
- spectral response measurements of at least one cell per group.

Additional measurements are applied if necessary, for example LBIC measurements to show influences of ingot position (middle / edge / corner) on the cell performance.

3.3 Learning curve

Presenting the learning curve, we show how important standardized processes are for a reliable baseline process. Experience in the baseline process can increase the reliability of experimental results.

![Learning Curve](image)

Figure 2: Learning curve: evolution of efficiency during the setup of the baseline run at the ISC Konstanz for mc-Si solar cells.

Improving the quality of the processes will lead to a learning curve which includes the failure and success of optimization tasks. In addition, external influences become visible. In the baseline runs, mc-Si material was used showing the influence of the material quality. As discussed in 3.1, it is necessary to use homogenized material over all runs. In the first baseline runs, only the groups within one experiment were including homogenized material. Figure 2 shows the learning curve while establishing the baseline run at the ISC Konstanz. The first runs showed moderate results, improving the efficiency failed mainly due to unstable processes. After establishing a good wafer and group tracking, stabilizing the single processes and optimizing the documentation, cell performance increased significantly. Today, it is possible to process mc-Si material at the ISC Konstanz at an industrial level. Meanwhile, the cell-efficiency in the baseline runs for 156×156 mm² mc-Si material is 16.2% in average.

4 EXPERIMENTS USING THE BASELINE RUN

Apart from testing the stability of processes, experiments are performed within the baseline process. In the following, different examples of experiments in the baseline run are shown.

4.1 The baseline run as experimental platform

Process optimization of one single process steps should be done separately from other changes in the baseline run sequence. Only if differing results can be directly related to variations in the process flow, the results are useful. The same procedure is used for material testing.

Within each experiment, a reference group according to the baseline run is processed. If baseline material is used as well, the results of the reference group can be compared to former baseline runs. Consequently, besides the relative difference in cell parameters between the groups, the absolute level of the experiment is shown.

4.2 Material testing

In research, well known wafer material is very important. At the ISC Konstanz, the baseline process is used to check incoming wafers. Therefore, an algorithm for testing wafer batches was developed.

As described in 3.1 and 4.1, a reference group with known material should always be used. If possible, material should be tested in respect of the ingot position. A comparison between baseline material and testing material should be accurate, according to the knowledge about the reference group. Then, the scattering of the testing data and its dependence on the ingot position has to be analyzed.

![Material Test](image)

Figure 3: This mc-Si material under test shows a large variation in $V_{OC}$. The fill factor did not show such a behavior.

4.3 Process stability

Steady drifts in processes are hard to detect in an experiment. Baseline runs early indicate differences in certain parameters from the normal values.

In an institute, it is literally impossible to use a statistical process control for monitoring process stability. The manifold reasons include low throughput, time consuming (non-inline) measurements, different project partners with resulting confidentiality and often-changing processes. Instead of trying the impossible, the baseline run is an efficient method to monitor process stability, offering the possibility to prevent failure of time consuming and costly experiments.

For example, a problem with the diffusion furnace occurred. During baseline experiments drifting homogeneities over the diffusion boat have been observed. Furthermore, the absolute sheet resistance level decreased about 13%, the diffusion tube had to be exchanged. Using the baseline run for monitoring this irregularity was detected. Afterwards an optimization was done by the baseline diffusion recipe, an advanced industrial emitter. The homogeneity over the diffusion
boat was optimized, figure 4 shows the optimization.

Figure 4: Emitter sheet resistance of different diffusions during diffusion optimization to targeted 62 Ω/sq and a deviation of +/- 2 Ω/sq (diffusion Dif 9).

4.4 Optimization the contact firing process

Stepwise optimization of processes is essential to achieve clear results and best processes. For this, multiple parameters of a process step are varied. One example is the optimization of the contact firing process for the mc-Si baseline run. In general, optimization is limited to testing different peak temperatures. The baseline run optimization offered the possibility to analyze more process dependencies. As indicator, fill factor and pseudo fill factor have been used.

The centrotherm belt furnace uses six heating zones. It was decided to change the temperatures in the heating zones three to six and the belt speed. Instead of testing all possible 54 parameter sets, the design of experiments approach (DoE) was applied, using the StatGraphics software. While keeping the reliability above 90%, the necessary parameter combinations could be reduced to 15. The results showed one optimum within the chosen parameter range and one interpolated optimum using higher peak temperatures at high belt speeds. Therefore, additional four parameter sets have been tested to verify that the best fill factor was not in the interpolated parameter range.

Optimized firing parameters have been found, increasing the fill factor by 0.5% (absolute). Furthermore, the dependencies on the belt furnace became visible. As expected, the firing result is mainly influenced by the heating zones five and six (peak temperatures), but also zone four in combination with the belt speed is important as shown in figure 5. The belt speed by itself has minor influence. The optimum combinations of two factors zone three and zone five/six is plotted in figure 6.

Figure 5: Pareto chart: Influence of the different parameters based on pseudo fill factor measurement. Only values above 2 are significant.

Figure 6: Contour plot: Optimal combination of the temperatures in zone 3 and zones 5/6 regarding pseudo fill factor. Belt speed and temperature of zone 4 are kept fixed.

5 CONCLUSIONS

A stable baseline run representing industrial production lines was established at the ISC Konstanz. Cell results and stability are comparable with industrial standard, even though the baseline process takes place in a much more complex environment than in a “single purpose” production line. By process optimization, average efficiencies for mc-Si solar cells of 16.2 % are achieved. Using the baseline run,

– the process stability can be monitored,
– material quality can be checked reliably and
– experiments for cell development can be performed and compared to a solid reference.

At the ISC Konstanz, it has been shown how useful a stable industrial baseline process can be in an institute environment. The industry partner and the institute gain a high development speed. Overall, comparable experimental results and fast transfer to industry lines is ensured.

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